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The 4 m International Liquid Mirror Telescope: A Brief History and Some Preliminary Scientific Results

Jean SURDEJ[1,*], Bhavya AILAWADHI[2,3], Talat AKHUNOV[4,5], Ermanno BORRA[6], Monalisa DUBEY[2,7], Naveen DUKIYA[2,7], Jiuyang FU[8], Baldeep GREWAL[8], Paul HICKSON[8], Brajesh KUMAR[2], Kuntal MISRA[2], Vibhore NEGI[2,3], Anna POSPIESZALSKA-SURDEJ[1], Kumar PRANSHU[2,9] and Ethen SUN[8]

[1] Institute of Astrophysics and Geophysics, University of Liège, Allée du Six-Août 19c, 4000 Liège, Belgium

[2] Aryabhatta Research Institute of observational sciencES (ARIES), Manora Peak, Nainital, 263001, India

[3] Department of Physics, Deen Dayal Upadhyaya Gorakhpur University, Gorakhpur, 273009, India

[4] National University of Uzbekistan, Department of Astronomy and Astrophysics, 100174 Tashkent, Uzbekistan

[5] Ulugh Beg Astronomical Institute of the Uzbek Academy of Sciences, Astronomicheskaya 33, 100052 Tashkent, Uzbekistan

[6] Department of Physics, Université Laval, 2325, rue de l'Université, Québec, G1V 0A6, Canada

[7] Department of Applied Physics, Mahatma Jyotiba Phule Rohilkhand University, Bareilly, 243006, India

[8] Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada

[9] Department of Applied Optics and Photonics, University of Calcutta, Kolkata, 700106, India

[*] Corresponding author: jsurdej@uliege.be

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Abstract

The present article is based upon an invited talk delivered at the occasion of the inauguration of the 4 m International Liquid Mirror Telescope (ILMT) which took place in Devasthal (ARIES, Uttarakhand, India) on 21st March 2023. We present hereafter a short history of the liquid mirror telescopes and in particular of the 4 m ILMT which is the first liquid mirror telescope entirely dedicated to astrophysical observations. We discuss a few preliminary scientific results and illustrate some direct CCD images taken during the first commissioning phase of the telescope. We invite the reader to refer to the series of ILMT poster papers published in these proceedings of the third BINA workshop for more details about the instrument, operation, first observations, performance and scientific results.

Keywords: ILMT, survey, telescope, inauguration, first light

1. A Brief History

The concept of a liquid mirror telescope can be traced back to the XVIIth century when Isaac Newton demonstrated that the surface of a spinning liquid takes the shape of a paraboloid, representing the perfect surface for focusing a beam of parallel light rays into a single point.

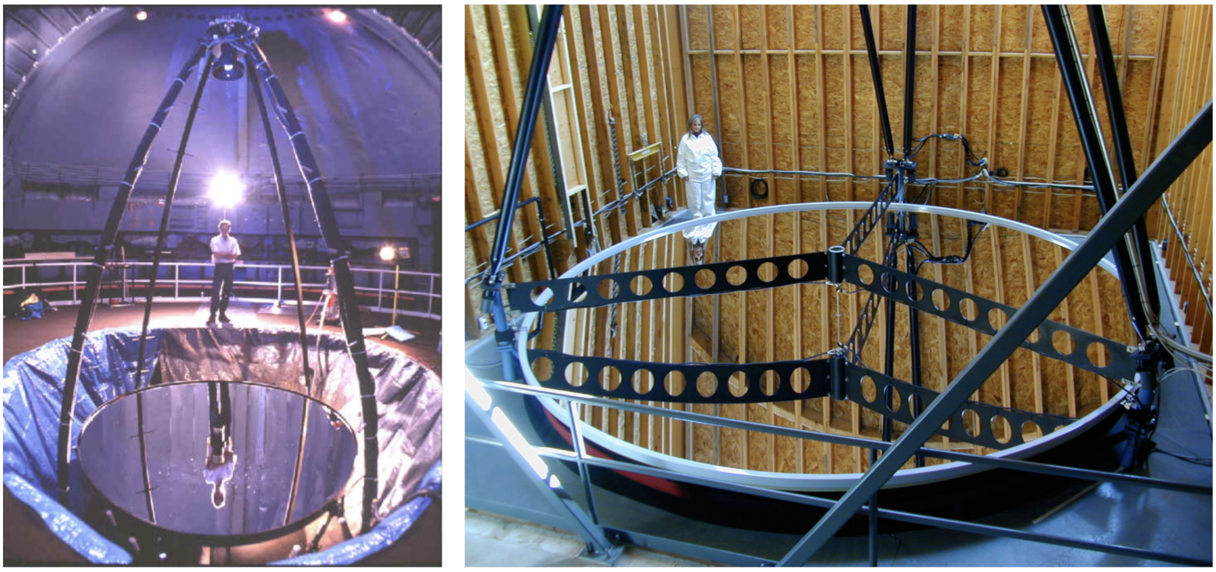
However, it was not until 1850 that an Italian astronomer, Ernesto Capocci, then director of Naples's observatory, revived the idea of using a rotating container filled with mercury as the primary mirror of an astronomical telescope (Capocci, 1850). At that time, the concept did not gain much interest, primarily because a mercury mirror cannot be tilted to track moving objects. Due to the Earth's rotation, astronomical objects would produce long streaks instead of clear stellar images on the photographic emulsions previously used in astronomy. Let us immediately point out that the advent of charge-coupled devices (CCDs) in the 1970s changed this situation. CCDs enabled a technique called time-delayed integration (TDI) to compensate for the Earth's rotation (Gibson and Hickson, 1992). This is achieved by electronically shifting the electronic charges on the surface of the CCD at the same speed as the stellar images drift in the focal plane of the telescope, thereby yielding sharp images. TDI has revived scientific interest in liquid mirrors.

But it was not until the end of the XIXth century that anyone tried to build a liquid mirror (LM). In 1875, Henry Skey of New Zealand built a ~ 35 cm LM in the laboratory. In 1909, Robert Wood constructed a 51 cm prototype at Johns Hopkins University (Baltimore, USA), and conducted first sky observations. However, annoying ripples appeared at the surface of the mercury because of vibration transmission and the difficulty of maintaining the angular rotation of the mirror constant.

Starting in the early 1980s, scientists, predominantly in Canada, embarked in significant development work in the laboratory and observatories. Researchers first demonstrated the feasibility of large liquid optics and developed the fundamental technology behind it. Optical shop tests of liquid mirrors with diameters as large as 2.5-m showed diffraction-limited optical quality. For instance, in 1982, Ermanno Borra proposed a solution to some of the technical challenges encountered by Robert Wood. Borra suggested dampening the vibrations that caused ripples by using a pressurized air-bearing to support the dish. Additionally, he suggested pouring a liquid resin on the dish surface first, allowing it to dry into the correct shape, then pouring reflective liquid onto it as a coating, diminishing at the same time the amount of mercury needed.

In 1994, Paul Hickson, Ermanno Borra and their colleagues built an experimental 2.7-m diameter liquid mirror telescope at the University of British Columbia (UBC) near Vancouver (see Fig. 1 and Hickson et al., 1994). Hickson also collaborated with NASA on a 3-m liquid mirror telescope in New Mexico for observing space debris (see Fig. 2(a) and Potter and Mulrooney, 1997). In early 2003, Hickson built the 6-m Large Zenith Telescope (LZT) to extend LM technology to larger apertures (see Fig. 2(b) and Hickson et al., 2007). Liquid mirrors have also been used by atmospheric scientists for LIDAR applications (Sica et al., 1995; Wuerker, 2002). For instance, the LZT provided unprecedented spatial and temporal resolution for studying the structure and dynamics of the Earth's mesosphere and lower thermosphere. The LZT was de-commissioned in 2016.

Figure 1: The UBC–Laval 2.7-m liquid mirror built in 1994 (© Prof. Paul Hickson).



(a) (b)

Figure 2: (a) The NASA Orbital Debris Observatory (NODO, 1995–2002, © Chip Simons Photography). (b) The Large Zenith Telescope (LZT, 2003–2016, © Prof. Paul Hickson).

All these LMTs were first-generation instruments, which were either not optimized for astronomy or not located at high-quality astronomical sites. The International Liquid Mirror Telescope (ILMT) has greatly benefited from all the previous technological advancements and has been specifically developed for astronomical research at a high-quality astronomical site.

The ILMT project was initially proposed during the *Science with LMTs* workshop organized by Prof. Ermanno Borra on April 14–15, 1997, at the Marseille Observatory in France. It finally materialized from a scientific collaboration in observational astrophysics involving the Liège Institute of Astrophysics and Geophysics (Liège University), several Canadian universities (British Columbia, Laval, Montréal, Toronto, Victoria and York) and the Aryabatta Research Institute of observational sciencES (ARIES, Nainital, India). Meanwhile, several colleagues from the Royal Observatory of Belgium, the Poznań Observatory (Poland), the Ulugh Beg Astronomical Institute of the Uzbek Academy of Sciences and the National University of Uzbekistan, and the Indian Space Research Organization (ISRO) also joined the ILMT project (Surdej et al., 2018, 2022).

After several years of design work and construction in Belgium by AMOS (Advanced Mechanical and Optical Systems, Liège), CSL (Centre Spatial de Liège), SOCABELEC (Jemeppe-sur-Sambre) and Liège University, as well as in India by ARIES, commissioning began in April 2022. The telescope achieved first light on April 29, 2022 (Kumar et al., 2022). The 4-meter ILMT is located on the ARIES site of Devasthal (Uttarakhand, India, Longitude = $79°41'07''.08$ E, Latitude = $29°21'41''.4$ N, Altitude = 2378 m). Its inauguration took place on the first day of spring in 2023, i.e. on March 21, 2023.

After this brief history on LMs (a more detailed and general account on the history of LMTs may be found in Gibson, 1991) and the ILMT project, we describe the very special type of optical corrector required for such a telescope and we also present some first scientific results.

2. Need for a Special Optical Corrector

But the fool on the hill,
Sees the Sun going down.
And the eyes in his head,
See the world spinning around . . .

The Beatles

But if we cannot orient the mirror of our telescope and given that the Earth rotates around its south-north axis, the stars in the focal plane must move. . . This leads us to the question: "What kind of trajectories do the stars follow?"

Since the light rays emitted by the stars sweep a conical surface (which degenerates into a plane perpendicular to the south–north axis in the special case of an equatorial star), these same light rays intersect, upon entering an optical system (cf. the aperture of the ILMT), the plane surface of the detector, following a conical trajectory (see Fig. 3). It can be demonstrated that

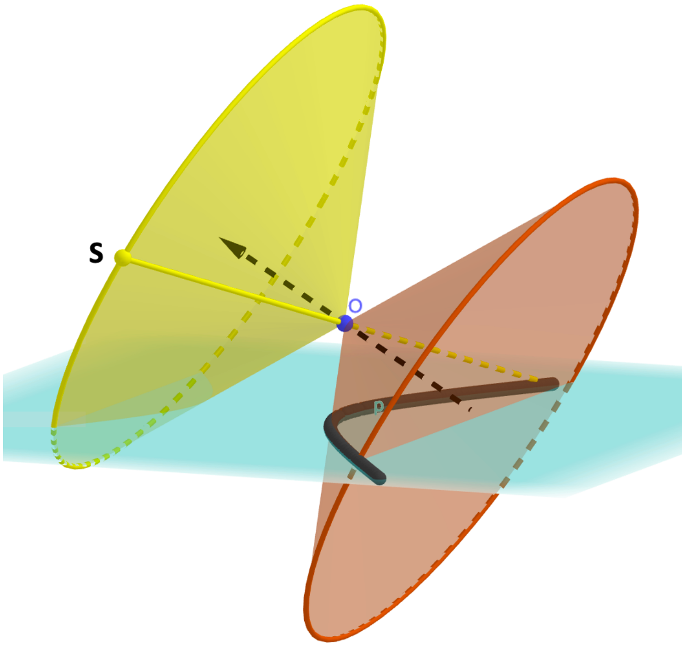
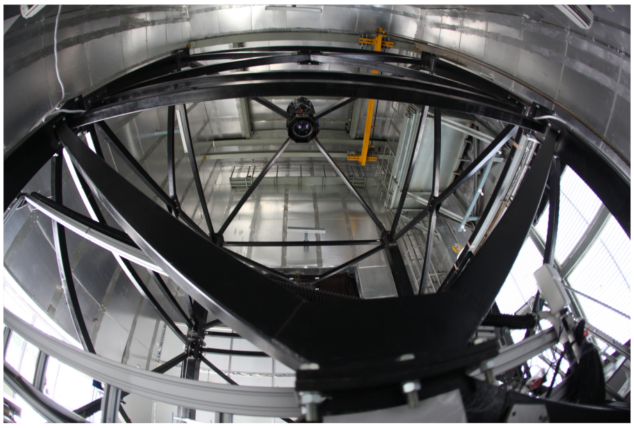


Figure 3: Due to the rotation of the Earth, the light rays emanating from the star S sweep a cone, with its directrix being a circle centered on the south-north axis (indicated by the dashed black vector) and its generatrix being the light ray itself. Upon entering the optical system at O (the vertex of the cone), the light rays intersect the plane of the CCD detector along a conical path, represented by the black bold curve, which is the branch of a hyperbola in the present case.

for a zenith telescope installed at a latitude of 45°, this conical trajectory corresponds to the branch of an hyperbola. It is also the fate of all the solar shadows cast on the ground or on walls to follow conical trajectories during daylight.

There is thus the need for a specialized optical corrector to be positioned in front of the CCD in order to render linear the hyperbolic trajectories of the stars in the focal plane of the ILMT. Such an optical corrector, known as the TDI optical corrector, consisting of five lenses, some of which are tilted and/or offset from the optical axis, has been designed by Hickson and Richardson (1998). Figure 4(a) provides a bottom view of the ILMT, where the optical corrector is visible at the top of the telescope's structure. Figure 4(b) illustrates the ILMT as seen from the top. One clearly sees the mirror covered with mercury. Several parallel mylar sheets covering the mirror are also visible; these sheets serve to protect the mercury surface from vortices generated by the rotation of the mirror in the air above it.

As mentioned earlier, it is now possible to take continuous images of the sky passing overhead by operating the CCD detector in TDI mode. For the ILMT, the effective exposure time is approximately 102 s, which is the time it takes for a star to cross the entire length of the CCD. Due to limitations of the data system, the maximum size of an individual image is 4096×40960 pixels, truncated to 4096×36864 pixels because the first 4096×4096 pixels correspond to the



(a)

(b)

Figure 4: (a) Fish-eye view from the bottom of the main ILMT structure showing the optical corrector at the very top. (b) Top view of the ILMT mirror, filled with mercury and covered with mylar.

ramping phase of the exposure. Consequently, there is a small gap between consecutive images while the data are being written to disk. The CCD detector is cooled down to a temperature near $-110\,^{\circ}$C in order to reduce dark current.

3. First Scientific Results

Thanks to the Earth's rotation, the telescope scans a strip of sky centered at a constant declination equal to the latitude of its location ($+29^{\circ}21'41.4''$ for the ARIES Devasthal Observatory). As the seasons change, this strip moves in and out of the galactic plane and, in April, passes very close to the northern galactic pole, an ideal region for the observation of extragalactic objects. The angular width of the strip is about $22'$, a size limited by that of the CCD detector (4096×4096 pixels) used in the focal plane of the telescope.

Since the ILMT observes the same region of the sky night after night, it is possible to either co-add the images taken on different nights to improve the limiting magnitude or subtract them from a high signal-to-noise (S/N) reference image to conduct a variability study of the corresponding strip of sky (Surdej et al., 2006). During the astronomy workshop in Marseille in 1997, some of us realized that a deep survey of such a narrow strip could potentially lead to the detection of some 20,000 quasars. Given that about one in every one thousand quasars is expected to exhibit multiple images due to gravitational lensing by a foreground galaxy, this could yield approximately 20 cases of multiply imaged quasars in the ILMT's field of view. Such findings would be invaluable for cosmologists, as they could use these systems to investigate the distribution of dark matter and the geometry and expansion history of the Universe. A cost-effective and dedicated instrument like the ILMT would be ideal for conducting such studies (Refsdal and Surdej, 1994).

Given the large diameter ($D = 4\,$m) and comparatively short effective focal length ($f = 9.44\,$m) of the ILMT, it serves as a powerful survey telescope. The detection threshold of any faint moving objects (such as asteroids, comets, space debris, ...) is proportional to the focal length and inversely proportional to the square of the mirror diameter. Therefore, it is not surprising that more than 80 human-made objects in Earth orbit, among which only about half are cataloged, were detected during ten nights of observation with the ILMT during the fall of 2022 (see the ILMT paper by Hickson et al. (2024) and Fig. 5(a)).

Similarly, some 75 known asteroids have been detected during nine consecutive nights in October–November 2022 within just one field, which had an angular extent of $22' \times 198'$, i.e. covered during ~ 15 minutes (see ILMT paper by Pospieszalska-Surdej et al. (2024), and Fig. 5(b)).

Finally, given the fast ratio $f/D \simeq 2.4$ of the ILMT, it serves as a highly sensitive instrument for detecting low surface brightness objects. This capability is exemplified by its ability to detect various astronomical phenomena, such as planetary nebulae (see Fig. 6), galaxies (see Fig. 7) including the potential detection of numerous supernovae (Borra, 2003; Kumar et al., 2018), interacting galaxies (see Fig. 8), as well as some impressive examples of reflection nebulae (see Figs. 9–11) and emission-line nebulae (see Fig. 12). Most of those images are composite frames captured through broadband ($\Delta\lambda \sim 150\,\mathrm{nm}$) g, r and i Sloan filters centered around the wavelengths λ 468.6 nm, 616.5 nm and 748.1 nm, respectively (Fukugita et al., 1996).

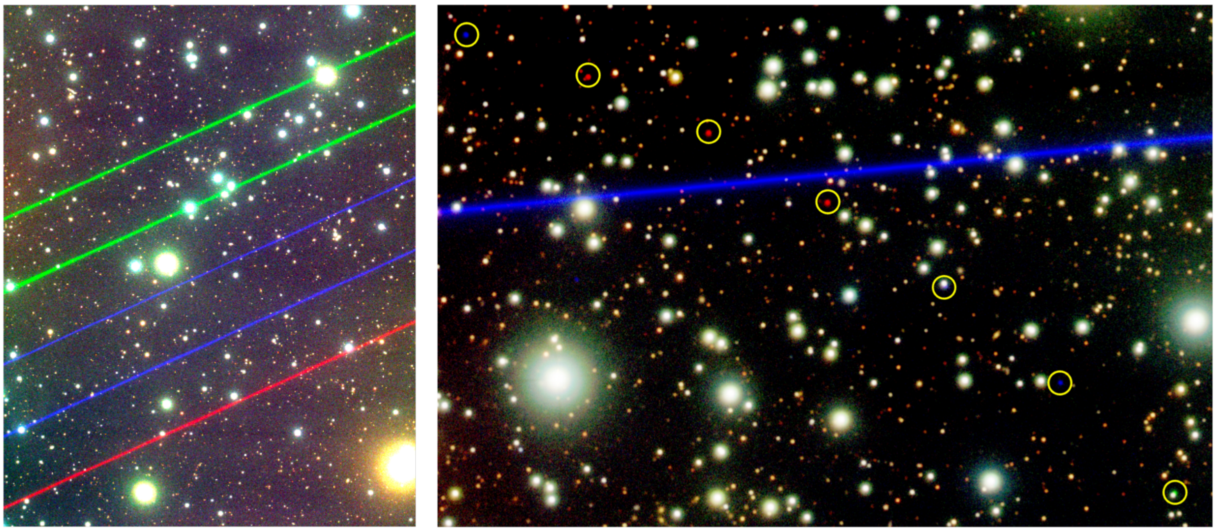
4. Conclusions

The ILMT is an instrument that can be entirely dedicated to a photometric and astrometric variability survey, as well as to the search for astronomical transients. Throughout the course of a year, it can image 117 square degrees of sky with a pixel size of $0.327''$ and an angular resolution that is not limited by the diffraction limit of the telescope but rather by the natural seeing conditions at the site (median FWHM $\simeq 1.2''$).

The main advantages of LMTs are numerous. Firstly, they offer the possibility of continuous observations at the zenith, where image quality is best, and atmospheric extinction as well as light pollution are smallest. It is also remarkable that a 1-D flat field can be generated from the median signal of the sky background recorded along each column of the CCD. This enables high-quality photometric calibration of the science frames.

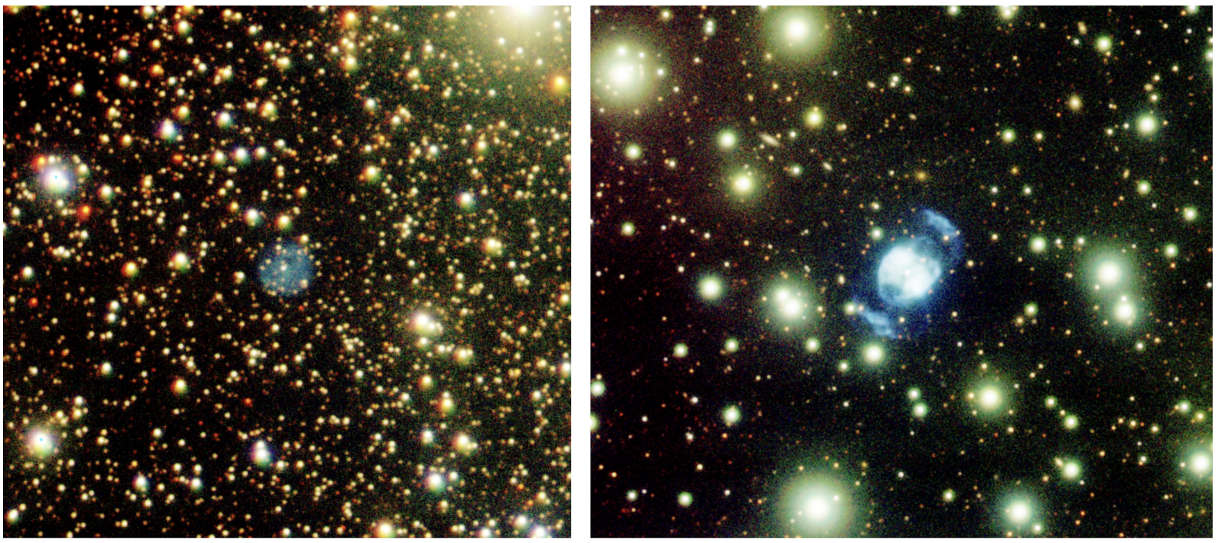
LMTs are also highly valued for their cost-effectiveness and ease of construction compared to conventional telescopes that rely on glass mirrors.

Among the disadvantages are the lack of steerability of LMTs and the limited integration time (102 s in the case of the ILMT). However, the co-addition of CCD frames acquired with the ILMT over subsequent nights allows the possible detection of very faint objects. Furthermore, image subtraction performed on a set of highly uniform CCD frames can reveal the appearance of faint transients. Applications of the ILMT include the detection and photometric follow-up of supernovae, multiply imaged quasars, variable stars, asteroids, low-surface-brightness objects, and space debris.



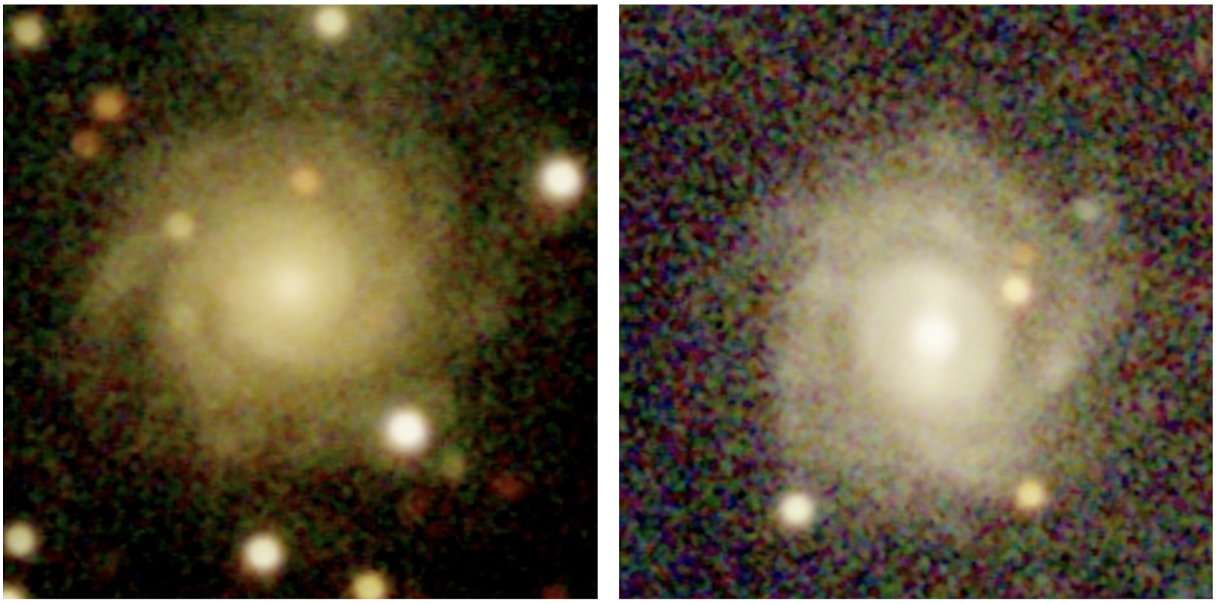
(a) (b)

Figure 5: (a) Composite image produced from five consecutive nights in October 2022 using the Sloan r, r, g, g and i filters successively. The diagonal streaks were caused by the non-active Russian communication satellite Meridian 3 (37212). (b) Example of an asteroid (3548 Eurybates) observed with the 4 m ILMT over seven consecutive nights in October 2022 using the Sloan g, r and i filters. The blue streak is caused by a passing satellite.



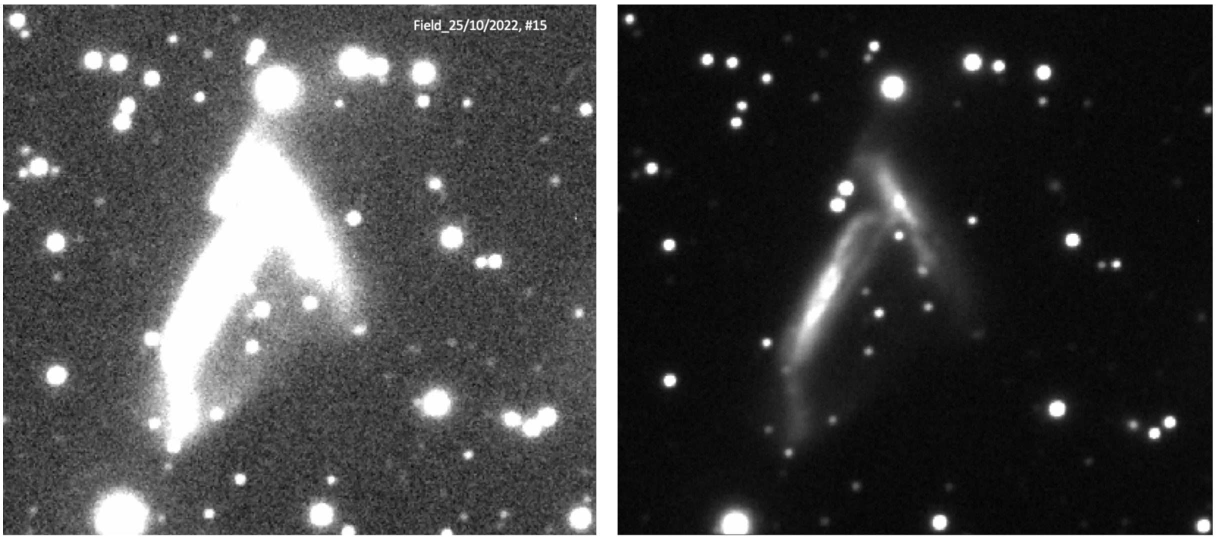
(a) (b)

Figure 6: (a) Composite image of the planetary nebula NGC 6842 in the field of view of the ILMT. (b) Composite g, r, and i image of the planetary nebula NGC 2371 in the field of view of the ILMT.



(a) (b)

Figure 7: (a) Composite g, r, i image of a field observed with the ILMT containing a nice spiral galaxy. (b) Composite g, r, i image of a field observed with the ILMT containing another spiral galaxy.



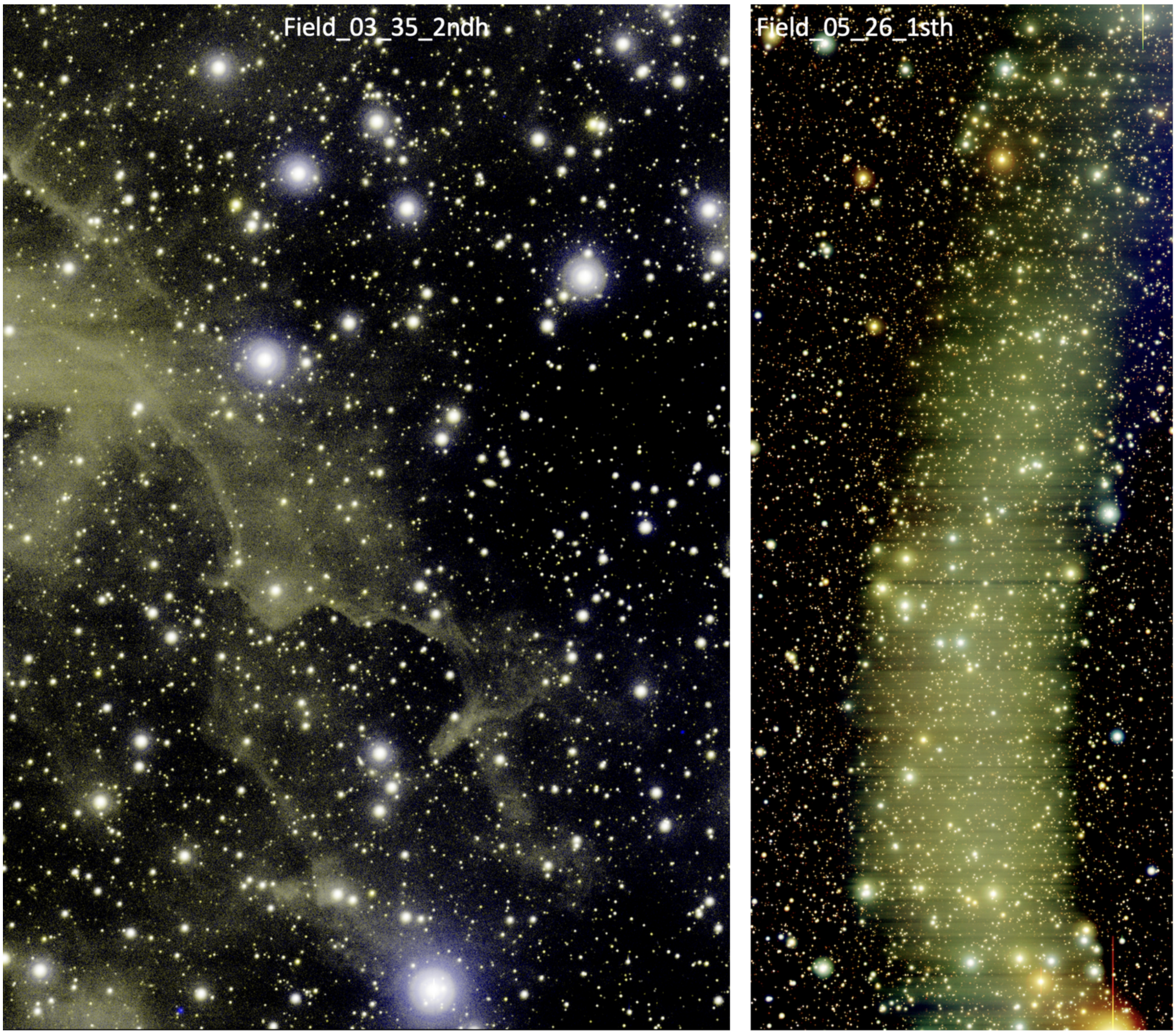
(a) (b)

Figure 8: (a) ILMT image in the i spectral band of a strange object, the physical nature of which is revealed in the right image after adjusting its dynamics. (b) Nice system depicting at least two interacting galaxies with material transfer between them.

(a)

(b)

Figure 9: (a) ILMT composite g, r, i image of a reflection nebula in one of the ILMT fields (near Local Sidereal Time (LST): LST = 04 h 12 m in October 2022). (b) ILMT composite g, r, i image of a reflection nebula in one of the ILMT fields (near LST = 04 h 12 m in October 2022).



(a) (b)

Figure 10: (a) ILMT composite g, r, i image showing a reflection nebula in one of the ILMT fields (near LST = 03 h 35 m in October 2022). (b) ILMT composite g, r, i image showing a reflection nebula in one of the ILMT fields (near LST = 05 h 26 m in October 2022).

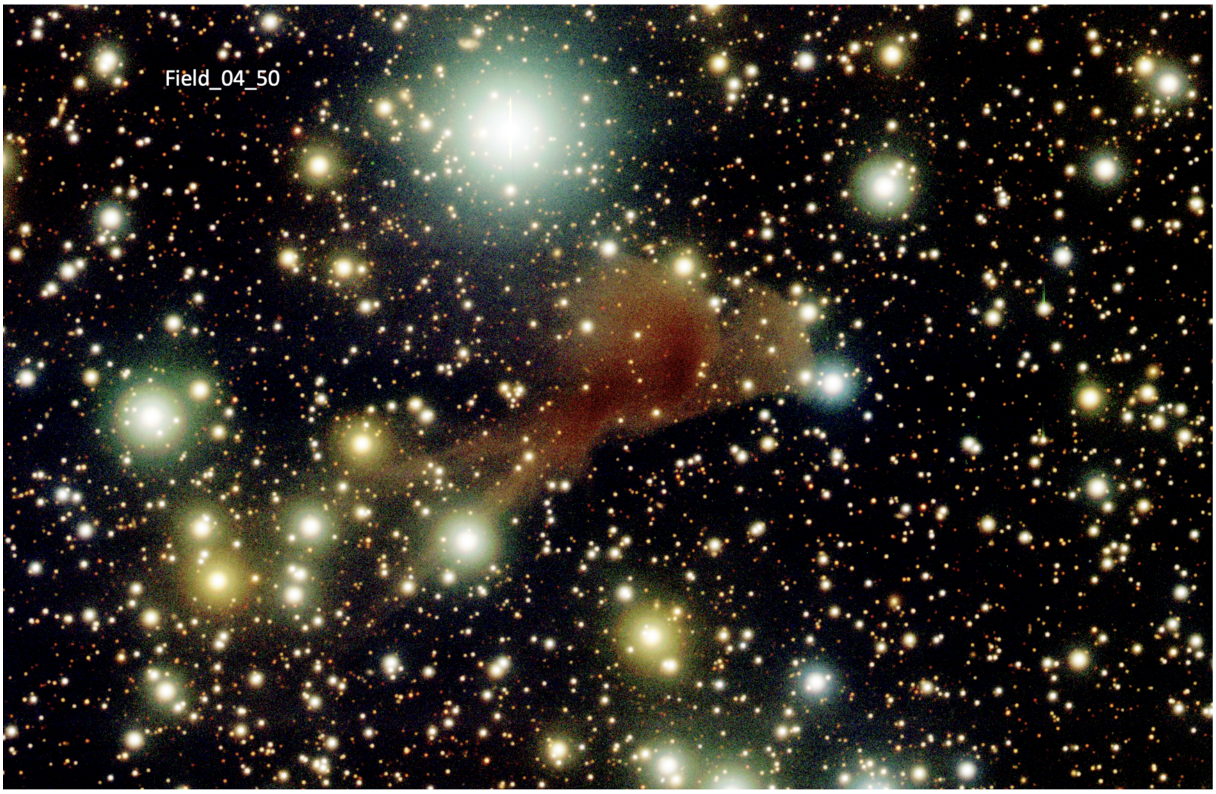
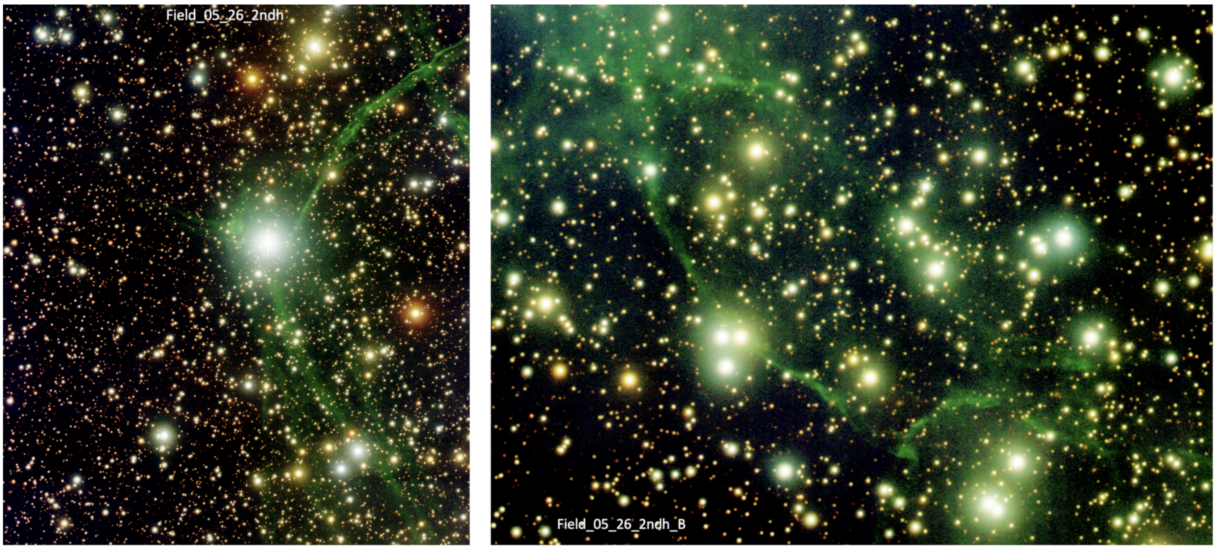


Figure 11: ILMT composite g, r, i image depicting a reflection nebula in one of the ILMT fields (near LST = 04 h 50 m in October 2022).



(a) (b)

Figure 12: (a) ILMT composite g, r, i image showing an emission-line nebula in one of the ILMT fields (near LST = 05h26m in October 2022). (b) ILMT composite g, r, i image depicting an emission-line nebula in one of the ILMT fields (near LST = 05 h 26 m in October 2022).

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Further Information

Authors' ORCID identifiers

0000-0002-7005-1976 (Jean SURDEJ)
0009-0000-1020-9711 (Bhavya AILAWADHI)
0000-0001-5115-6310 (Talat AKHUNOV)
0000-0003-4723-7614 (Ermanno BORRA)
0009-0002-2621-6611 (Monalisa DUBEY)
0000-0002-0394-6745 (Naveen DUKIYA)
0009-0006-1895-7048 (Jiuyang FU)
0000-0002-8289-8242 (Paul HICKSON)
0000-0001-7225-2475 (Brajesh KUMAR)
0000-0003-1637-267X (Kuntal MISRA)
0000-0001-5824-1040 (Vibhore NEGI)
0009-0005-3754-2094 (Anna POSPIESZALSKA-SURDEJ)
0009-0005-3844-3426 (Kumar PRANSHU)
0000-0003-3098-5835 (Ethen SUN)

Author contributions

This work results from a long-term collaboration to which all authors have made significant contributions.

Conflicts of interest

The authors declare no conflict of interest.

References

Borra, E. F. (2003) Cosmology at low redshifts. A&A, 404, 47–55. https://doi.org/10.1051/0004-6361:20030487.

Capocci, E. (1850) Letter to the Royal Academy of Sciences in Brussels, Belgium. Read at a meeting on 2 November 1850.

Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K. and Schneider, D. P. (1996) The Sloan Digital Sky Survey photometric system. AJ, 111, 1748. https://doi.org/10.1086/117915.

Gibson, B. K. (1991) Liquid Mirror Telescopes: History. JRASC, 85, 158–171. https://ui.adsabs.harvard.edu/abs/1991JRASC..85..158G.

Gibson, B. K. and Hickson, P. (1992) Time–delay integration CCD read–out technique: Image deformation. MNRAS, 258(3), 543–551. https://doi.org/10.1093/mnras/258.3.543.

Hickson, P., Ailawadhi, B., Akhunov, T., Borra, E., Dubey, M., Dukiya, N., Fu, J., Grewal, B., Kumar, B., Misra, K., Negi, V., Pranshu, K., Sun, E. and Surdej, J. (2024) Serendipitous detection of orbital debris by the International Liquid Mirror Telescope: First results. BSRSL, 93(2), 903–909. https://doi.org/10.25518/0037-9565.11920.

Hickson, P., Borra, E. F., Cabanac, R., Content, R., Gibson, B. K. and Walker, G. A. H. (1994) UBC/Laval 2.7 meter liquid mirror telescope. ApJ, 436, L201–L204. https://doi.org/10.1086/187667.

Hickson, P., Pfrommer, T., Cabanac, R., Crotts, A., Johnson, B., de Lapparent, V., Lanzetta, K. M., Gromoll, S., Mulrooney, M. K., Sivanandam, S. and Truax, B. (2007) The Large Zenith Telescope: A 6 m liquid-mirror telescope. PASP, 119, 444–455. https://doi.org/10.1086/517621.

Hickson, P. and Richardson, E. H. (1998) A curvature-compensated corrector for drift-scan observations. PASP, 110(751), 1081–1086. https://doi.org/10.1086/316230.

Kumar, B., Kumar, H., Dangwal, K. S., Rawat, H., Misra, K., Negi, V., Jaiswar, M. K., Dukiya, N., Ailawadhi, B., Hickson, P. and Surdej, J. (2022) First light preparations of the 4m ILMT. JAI, 11, 2240003. https://doi.org/10.1142/S2251171722400037.

Kumar, B., Pandey, K. L., Pandey, S. B., Hickson, P., Borra, E. F., Anupama, G. C. and Surdej, J. (2018) The zenithal 4-m International Liquid Mirror Telescope: a unique facility for supernova studies. MNRAS, 476(2), 2075–2085. https://doi.org/10.1093/mnras/sty298.

Pospieszalska-Surdej, A., Ailawadhi, B., Akhunov, T., Borra, E., Dubey, M., Dukiya, N., Fu, J., Grewal, B., Hickson, P., Kumar, B., Misra, K., Negi, V., Pranshu, K., Sun, E. and Surdej, J. (2024) Detection and identification of asteroids with the 4 m ILMT. BSRSL, 93(2), 941–947. https://doi.org/10.25518/0037-9565.11931.

Potter, A. E. and Mulrooney, M. (1997) Liquid metal mirror for optical measurements of orbital debris. AdSpR, 19(2), 213–219. https://doi.org/10.1016/S0273-1177(97)00003-3.

Refsdal, S. and Surdej, J. (1994) Gravitational lenses. RPPh, 57(2), 117–185. https://doi.org/10.1088/0034-4885/57/2/001.

Sica, R. J., Sargoytchev, S., Argall, P. S., Borra, E. F., Girard, L., Sparrow, C. T. and Flatt, S. (1995) Lidar measurements taken with a large-aperture liquid mirror. 1. Rayleigh-scatter system. AO, 34(30), 6925–6936. https://doi.org/10.1364/AO.34.006925.

Surdej, J., Absil, O., Bartczak, P., Borra, E., Chisogne, J.-P., Claeskens, J.-F., Collin, B., De Becker, M., Defrère, D., Denis, S., Flebus, C., Garcet, O., Gloesener, P., Jean, C., Lampens, P., Libbrecht, C., Magette, A., Manfroid, J., Mawet, D., Nakos, T., Ninane, N., Poels, J., Pospieszalska, A., Riaud, P., Sprimont, P.-G. and Swings, J.-P. (2006) The 4m international liquid mirror telescope (ILMT). In Ground-based and Airborne Telescopes, edited by Stepp, L. M., vol. 6267. International Society for Optics and Photonics, SPIE. https://doi.org/10.1117/12.671695.

Surdej, J., Hickson, P., Borra, E., Swings, J.-P., Habraken, S., Akhunov, T., Bartczak, P., Chand, H., De Becker, M., Delchambre, L., Finet, F., Kumar, B., Pandey, A., Pospieszalska, A., Pradhan, B., Sagar, R., Wertz, O., De Cat, P., Denis, S., de Ville, J., Jaiswar, M. K., Lampens, P., Nanjappa, N. and Tortolani, J.-M. (2018) The 4-m International Liquid Mirror Telescope. BSRSL, 87, 68–79. https://doi.org/10.25518/0037-9565.7498.

Surdej, J., Hickson, P., Kumar, B. and Misra, K. (2022) First light with the 4-m International Liquid Mirror Telescope. Physics News, 52, 25–28.

Wuerker, R. F. (2002) Arctic lidar at Univ. of California/Los Angeles' HIPAS Observatory. In Optical Spectroscopic Techniques, Remote Sensing, and Instrumentation for Atmospheric and Space Research IV, edited by Larar, A. M. and Mlynczak, M. G., vol. 4485, pp. 292–302. SPIE. https://doi.org/10.1117/12.454264.